Uncontrolled H^0 Excited-State Losses For SNS Injection

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INTRODUCTION

Uncontrolled beam loss is a major concern for the Spallation Neutron Source, SNS. For hands on maintenance a full-energy beam loss of less than 1 nA/m is required. This requirement corresponds to an integrated uncontrolled beam loss in the accumulator ring of less than 2 x 10^{-4} for the1-MW initial case and less than 1 x 10^{-4} the 2-MW upgraded case. A potential source of large uncontrolled beam losses arises from decay of neutral hydrogen atoms in excited states, which are formed in the injection process using an H- stripping foil [1]. This technical note addresses the excited state neutral hydrogen (H^{o*}) loss issue for the SNS injection scheme which uses a new idea of locating the stripping foil in a decreasing magnetic field.

The loss process is shown schematically in Figure 1. Most of the accelerated H^- ions are stripped to H^+ ions by a 200-400 μg/cm^2 carbon stripper foil[1]; however, a small percentage are only partially stripped and exit the foil as neutral H^o atoms in excited states. After traversing the foil only about 10^{-7} of the initial H^- ions remain as H^- ions. The injection system maybe designed such that about 1% of the incoming H^- ions purposely miss the foil allowing the foil size to be a final collimator. In any case the H^-, H^o and H^+ must be separated by a magnetic field. The H^o are not all in the ground state. The neutrals are distributed amongst the allowed excited states following an $n^{-2.8}$ law, where n is the principle quantum number of H^o atoms. Because the H^o must pass through a magnetic field, the excited neutrals can be stripped to H^+ by the Stark effect. For magnetic field levels considered here, the higher excited states with $n \geq 6$ have short stripping lifetimes and decay practically instantaneously after the foil and are captured into the ring acceptance along with the fully stripped H^+ ions. The lower excited states with $n \leq 3$ have long stripping lifetimes and survive long enough to be transported along with the ground state H^o into an injection beam dump and are a controlled loss. However, the $n = 4$ and 5 states have the potential of decaying in flight in the magnetic field to H^+ ions far enough downstream from the injection foil such that their resultant deflection puts them on trajectories that do not lie within the ring acceptance. This process can lead to an appreciable uncontrolled beam loss leading to activation of accelerator components.

The SNS has a four-fold FODO lattice with achromatic straight sections [2]. One straight section will be dedicated to injection. The equilibrium orbit at injection will be initially offset by 8.0 cm with a chicane consisting of three dipoles. The chicane will be located in the ring such that the central F quadrupole of the straight section will be between the second and third dipole. Eight time varying bump magnets will be employed to phase-space paint the linac beam in both the horizontal and vertical directions into the ring acceptance. For the SNS, the injection foil will be situated in the falling fringe field of the second chicane dipole. The falling dipole field will give the beam a 46 T-mm bend. This configuration of having the H^{o*} recoil into a falling magnetic field minimizes the

[1] This design decision is still under consideration.

uncontrolled beam loss. We calculate that less than 10^{-4} of the n = 4 and 5 excited state neutrals will be uncontrollably lost, which corresponds to less than $3x10^{-7}$ of the total beam. This arrangement results in a smaller loss fraction compared to situating the foil in a constant magnetic field. In addition, the present SNS injection scheme reduces the loss sensitivity to the exact foil placement and to uncertainties in the calculation of excited state lifetimes.

CALULATION

The model used to calculate the H^{o*} loss is simple, and similar to that used in Ref. 3. In particular, excited state H^{o*} lifetimes are calculated as a function of magnetic field using an analytic 5th order expansion formula from Ref. 4. Lifetimes are calculated for each of the allowed states for principle quantum numbers n= 4 (10 sub-states) and n=5 (15 sub-states). The populations are distributed as $n^{-2.78}$ amongst the principle quantum number n states, and within each principle quantum state they are uniformly distributed amongst sub-states. Each sub-state is tracked longitudinally down a prescribed magnetic field profile, with its lifetime $\tau(n,n1,n2,m)$ being continually updated. The population of each state is reduced by $\exp(-\Delta t/\tau)$ each longitudinal step ds, where Δt is the time increment associated with ds. Surviving particle population levels are calculated at a given point by summing the remaining populations of all the states. The difference between the calculated surviving population and the original population indicates how much H^{o*} beam has been lost up to that point. The tracking proceeds until the prescribed magnetic field is zero, or a prescribed horizontal bend angle has been exceeded.

The total magnetic deflection experienced by fully stripped H^+ is also tracked by integrating ds/ρ from the foil, where ρ is the H^+ bending radius. For a prescribed critical deflection angle, which we refer to as the loss criteria, the loss fraction can be calculated by determining the difference of the remaining H^{o*} population at the longitudinal position corresponding to the critical deflection and the population at the final field location. For the SNS, this critical deflection angle is set at 1.0 mrad. Figure 2 shows the relationship between the injected linac phase-space ellipse and the target for the final ring ellipse. This case is for the nominal linac beam rms emittance of 0.14 π-mm-mrad and ring beam full emittance of 120 π-mm-mrad. There is about 1 mrad available between a possible linac spot and the desired ring acceptance. This defines the loss criteria for SNS.

CALCULATION BENCHMARK

Lifetimes verses magnetic field level for 800 MeV and 1000 MeV excited state H^o beams are shown in Figures 3 and 4 respectively. The curves for the 800 MeV case agree with those in Ref. 3. These lifetimes are also close to those in Ref. 5. The gap between the n= 4 and 5 states is at a slightly lower (~ 0.025T) for the 1000 MeV case.

A calculation from Ref. 3 was reproduced as an initial check of the loss calculation. This is for the case of an 800 MeV H^- beam, and a stripping foil located in a constant magnetic field with a dipole length corresponding to a 5 degree bend of the beam.

The loss fractions for different field levels are calculated and shown in Figure 5. As in Ref. 5, the calculation was done for loss criteria of 2 and 3 mrad. The solid curves in Figure 5 are calculated using equation 67 in Ref. 4 for the lifetimes, which is the default method we use. The dashed curves are calculated using equation 72 from Ref. 4, which is a semi-empirical approximation to equation 67. The results found using the different lifetime approximations are similar, and bracket those from Ref. 3.

SNS INJECTION

For SNS, the injection foil will be situated in the falling fringe field of a dipole magnet. The falling field is from a 0.31 T dipole with a 20 cm gap. After passing through the foil, any neutral H^{o*} are exposed to a continually decreasing magnetic field. We choose a longitudinal position in the fringe field which has a magnetic field around 0.25 T, corresponding to the gap between the $n = 4$ and 5 states. The shorter lived $n = 5$ states quickly decay and are lost near the foil. As the beam continues downstream, the remaining $n = 4$ state constituent lifetimes increase, thus reducing their probability of stripping away from the foil. The fringe field in the injection foil region for the SNS injection chicane dipole is shown in Figures 6-7 and is for a tapered dipole. H^{o*} loss fractions calculated for this field are shown in Figure 8. For the nominal SNS loss criteria of 1 mrad and foil location of 875 mm from the edge of the dipole, the uncontrolled losses are about 10^{-4} of the $n = 4$ and 5 state populations. This result is not very sensitive to the exact foil placement as compared to the results of a foil in a constant field as shown in Figure 8. Furthermore, compared to the constant field case in Figure 5 the loss fraction is about 100 times lower, for an equivalent loss criteria. A separate magnet channel as proposed in Ref. 3 does reduce the losses for that case by a factor of 10, but this method is highly sensitive to the exact field level of the separate magnet channel.

The actual H^{o*} loss as a percentage of the total injected beam population is smaller than the levels shown in Fig. 8. For a typical foil thickness, only 1 to 10% of the beam remains as H^o after passing through the foil, and of this 1 to 10% only about 2.5% of these neutrals are in the $n = 4$ and 5 states. Consequently the uncontrolled loss fraction arising from the stripping of the H^{o*} $n = 4$ and 5 state outside of the ring acceptance is $< 10^{-6}$ of the injected beam for SNS.

We have also calculated uncontrolled losses using a sharp-edged dipole, with the same peak field as the above tapered-edge dipole (see Fig. 6 for the field profile). Results for this case are shown in Fig. 9. The foil must be placed at a position of about 24 mm inside the dipole edge to achieve the required bend of 46 T-mm. In this case almost 10^{-3} of $n = 4$ and $n = 5$ H^{o*} ions are stripped beyond the 1-mrad loss criteria. This is about 10 times more loss than the corresponding tapered case. For the sharp-edge dipole, the foil must be placed in a higher field region in order to obtain enough bending, which is less optimal with regard to starting in a position in the gap between $n = 4$ and 5 states.

SENSITVITY TO RESULTS FOR LIFETIME CALCULATIONS

The H^{o*} lifetimes shown in Figures 3 and 4 are extremely sensitive to the magnetic field level. The low loss rates calculated here result from positioning the foil such that the field experienced by the H^{o*} is initially in the gap region between the n = 4 and 5 states. In the gap the n = 4 states have a very long lifetime and the n = 5 states have a very short lifetime, which minimizes the number of lost protons. In this section, sensitivities to our results are examined for an artificial case with no such gap. The lifetime shape with field of the (4,0,3,0) H^o excited state is evenly distributed amongst 25 artificial excited states ranging from the shortest lived n = 5 state and longest lived n = 4 state, as shown in Figure 10. Also we evenly distribute the population among these curves. The calculations shown in Figures 5 and 8 are repeated using these uniformly distributed lifetimes.

As show in Figure 11, without a gap about 13% of the n = 4 and 5 excited state H^o are lost for the case in a foil situated in a constant magnetic field (as per the calculation shown in Figure 5). This is about 50 times more loss than the case with a gap. As expected, the losses are not sensitive to the exact field level for the uniformly distributed H^{o*} states. Loss fractions using the uniformly spaced lifetimes for a foil situated in a tapered-edge dipole, similar to the calculation shown in Figure 8, are shown in Figure 12. Losses calculated here are about 100 times higher compared to the equivalent calculations in Figure 8, but are still lower than those shown in Figure 11.

SUMMARY

This technical note has addressed the excited state neutral hydrogen decay loss issue for the SNS injection scheme. A simple code was written and verified by reproducing the results of Ref. 3. A new scheme, which uses the idea of locating the stripping foil in a decreasing magnetic field, has been studied. The results of this study are summarized in Table 1. Using the nominal excited state lifetimes calculations, for SNS less than 10^{-4} of the n=4 and 5 excited state neutrals will be uncontrollably lost, which corresponds to $3x10^{-7}$ to $3x10^{-8}$ of the beam, depending on foil thickness. Positioning the foil in a decreasing magnetic field results in uncontrollable loss rates 100 times lower than those for the scheme in Ref. 3, using a foil in a constant magnetic field.

Locating the foil in the falling field of a dipole edge reduces the resulting angular separation between the H^- , H^o and H^+ beams, which must be accommodated. The present calculations assume the foil is in the falling field of a 0.31 T dipole with a 20 cm gap. This gives rise to a total bend of 46 mm-T, which is adequate for the SNS injection scheme. In addition, this injection scheme reduces the loss sensitivity to the exact foil placement and to uncertainties in the excited state lifetimes.

With the present SNS injection scheme, the uncontrollable beam loss for H^{0*} excited state decay will be reduced to a negligible loss level < $3x10^{-7}$ of the captured beam, even for the case of a thin 200 μg/cm^2 foil.

Table 1. Summary of uncontrollable loss fractions of the various cases investigated here.

Case	Fraction passing through foil as H^o [a]	Fraction of H^o in n=4 and 5 states	Fraction of n=4 and 5 states lost uncontrollably	Total loss fraction
SNS nominal[b]	0.01→0.1	0.026	10^{-4}	$3x10^{-7} \rightarrow 3x10^{-8}$
SNS[b] with uniformly distributed states	0.01→0.1	0.026	0.017	$4x10^{-5} \rightarrow 4x10^{-6}$
Constant Field [c]	0.01→0.1	0.026	$2.5x10^{-3}$	$7x10^{-6} \rightarrow 7x10^{-7}$
Constant Field [c] with uniformly distributed states	0.01→0.1	0.026	0.13	$3x10^{-4} \rightarrow 3x10^{-5}$

Notes for Table 1:
(a) - Depends on foil thickness.
(b) - Foil located in falling field of a tapered dipole, with a 0.46^{O} bend.
(c) – Scheme proposed in Ref. 3, with the foil in a constant dipole field, a 5^{O} bend and no additional corrector magnet.

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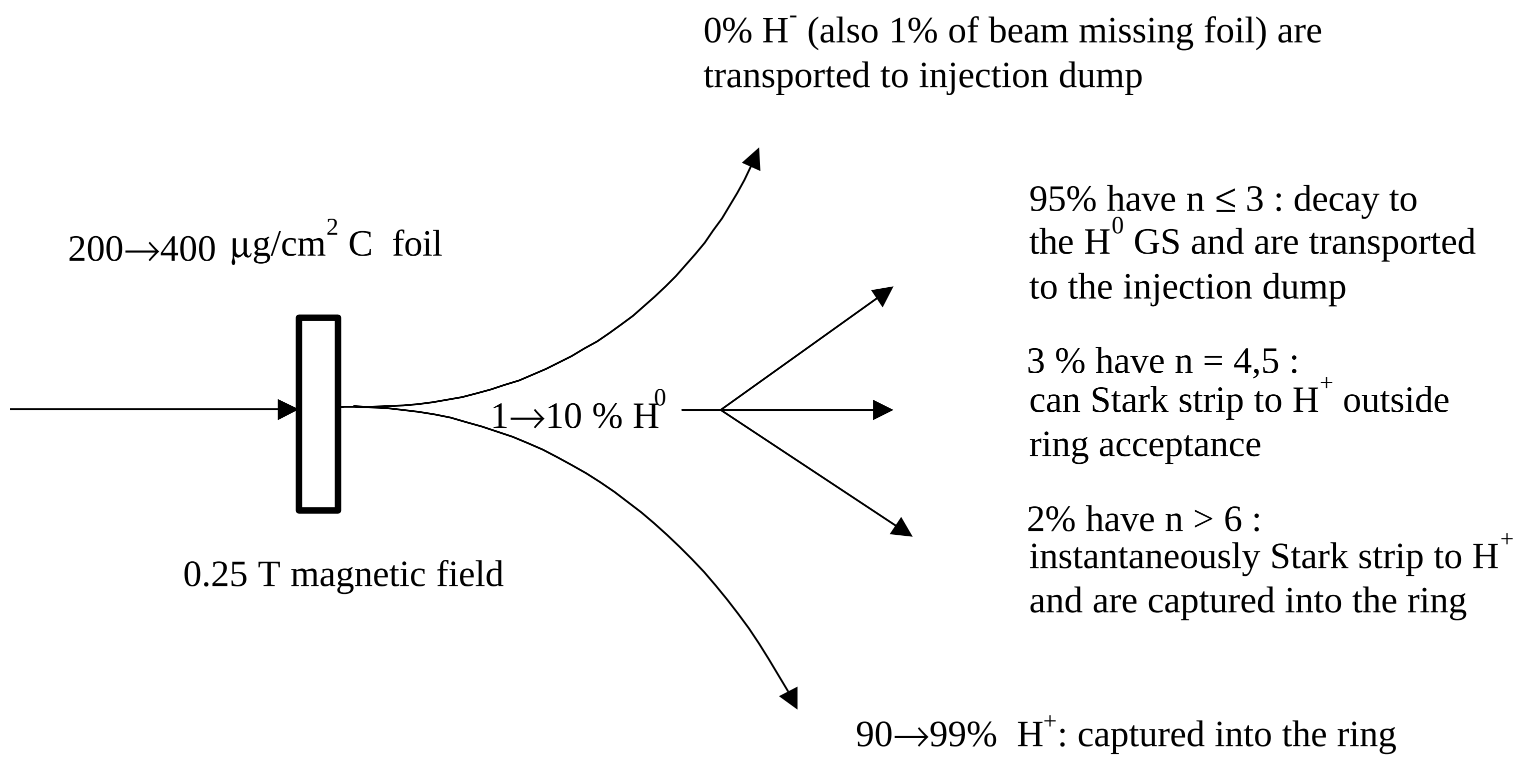

Fig.1 Schematic of the SNS foil injection process, and the resultant H^o loss channels.

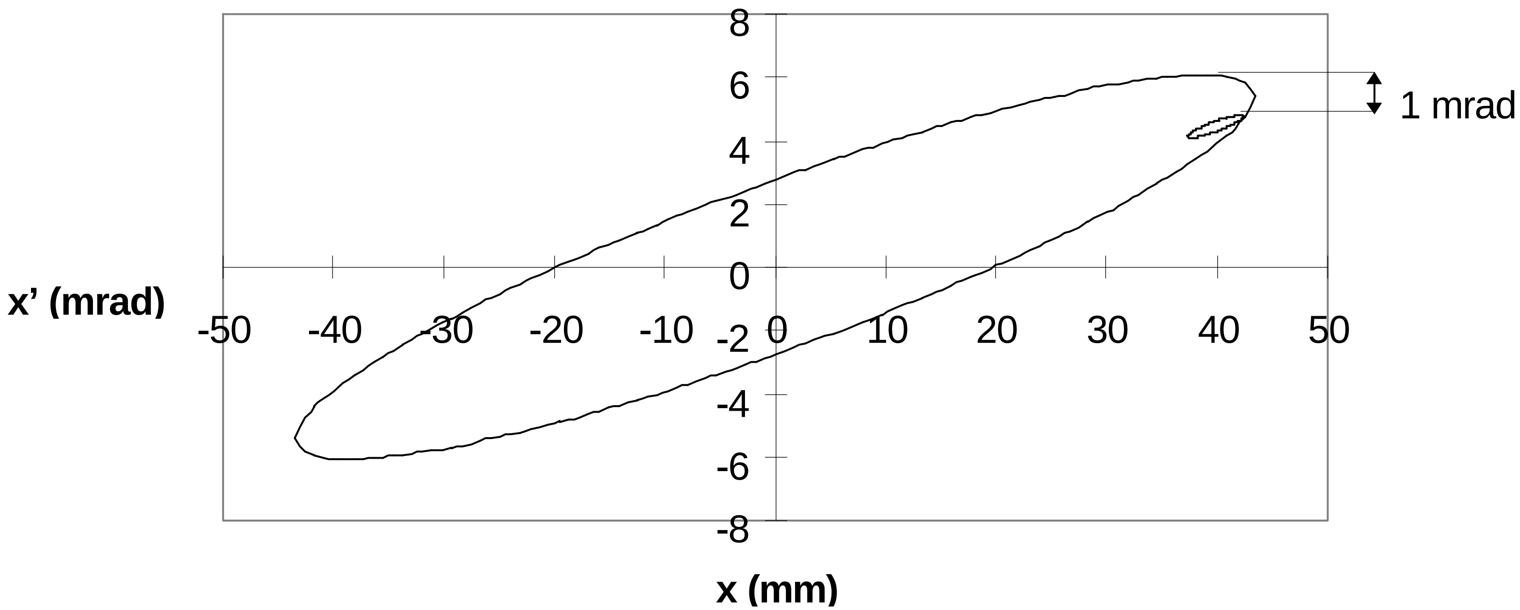

Fig. 2 Relationship between the linac beam horizontal emittance (small ellipse) and final ring emittance (large ellipse). There is about 1 mrad available for additional deflection between a possible beam location and the ring emittance. Both ellipses have β=15.7m and α = -1.96

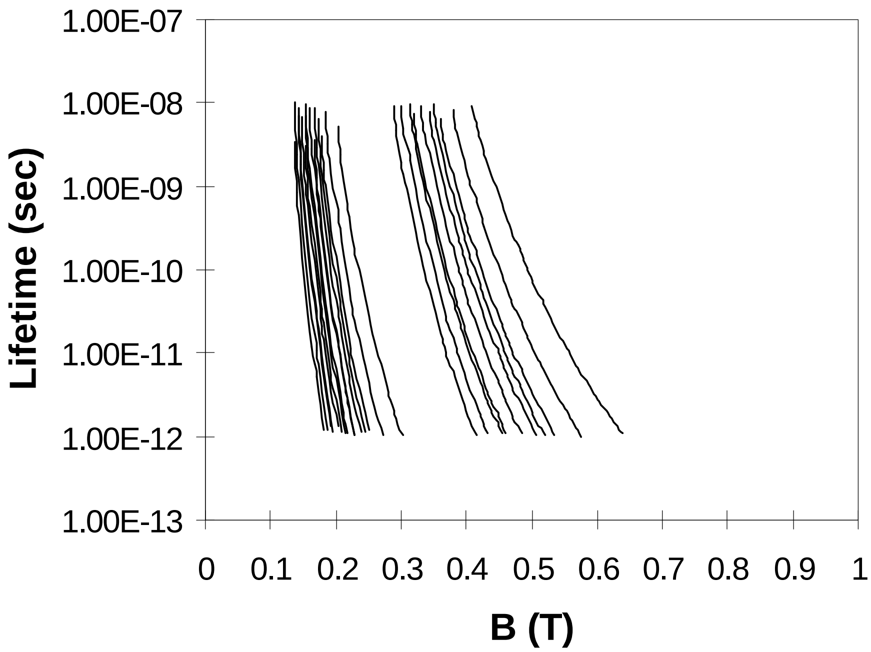

Fig. 3   Lifetimes for 800 MeV *n* = 4 (band at right) and *n* = 5 (band at left) excited state H^o verses magnetic field level.

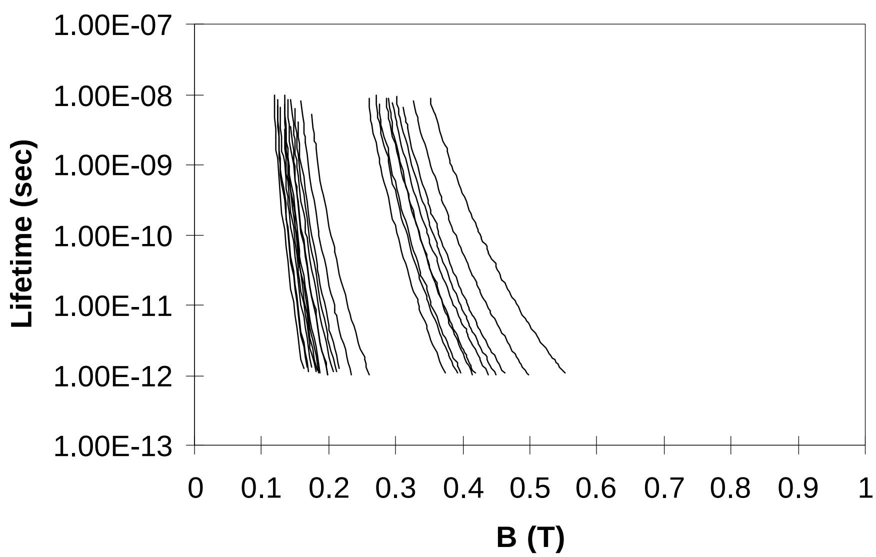

Fig. 4   Lifetimes for 1000 MeV *n* = 4 (band at right) and *n* = 5 (band at left) excited state H^o verses magnetic field level.

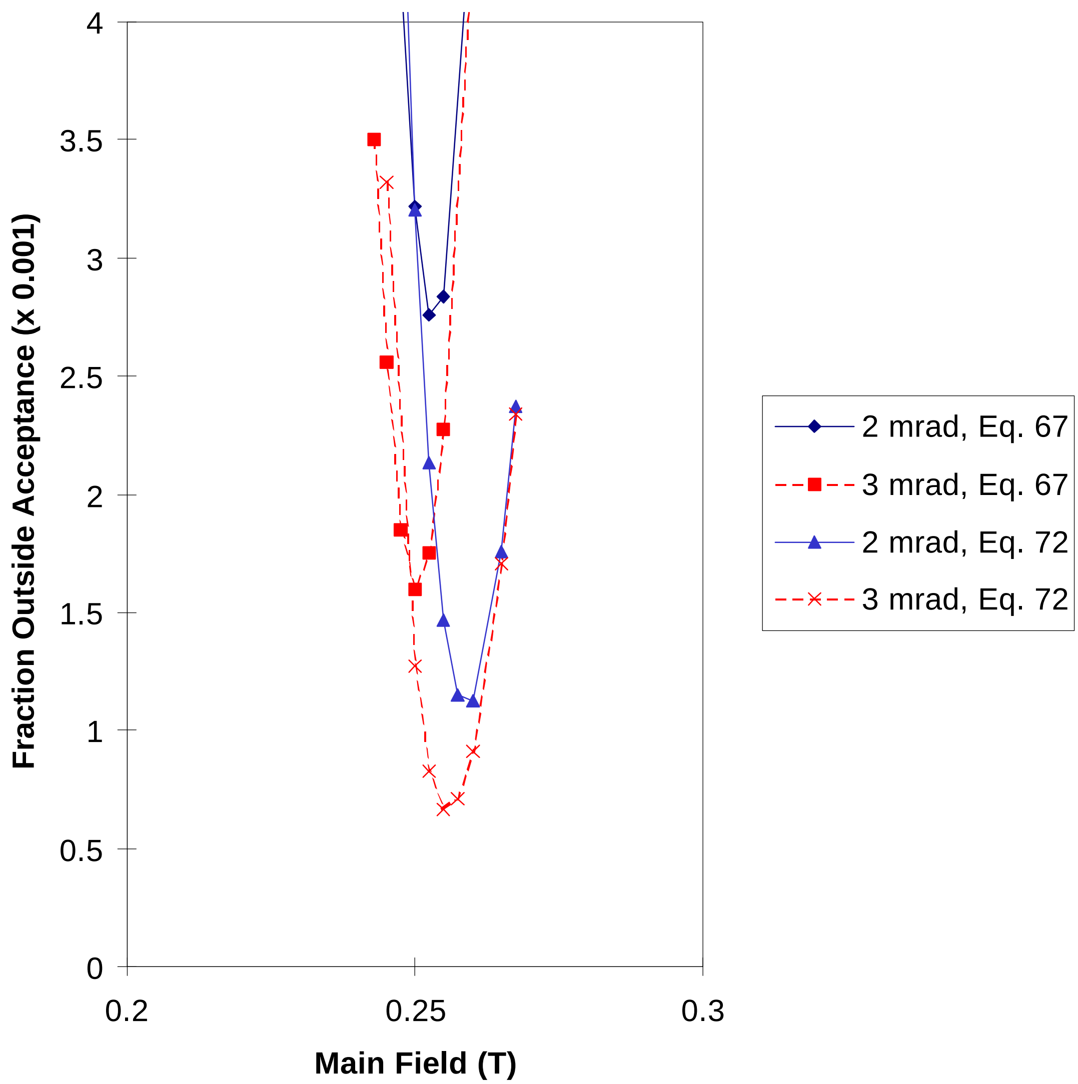

Fig. 5 Fraction of the beam which is stripped in a region outside of a prescribed loss criteria of 2 and 3 mrad verses constant magnetic field level. Calculations are shown for two different lifetime approximations from Ref. 4. The results compare well with those from Ref. 3.

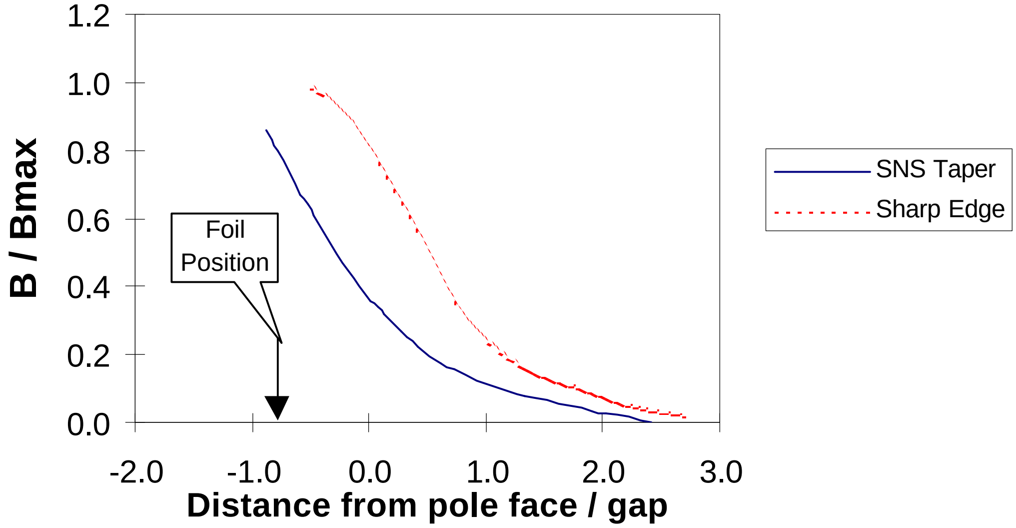

Figure 6 Magnetic field profiles in the nominal SNS injection dipole with a tapered edge. The foil position is indicated with an arrow. Also shown is the field profile for the case of a sharp edged dipole.

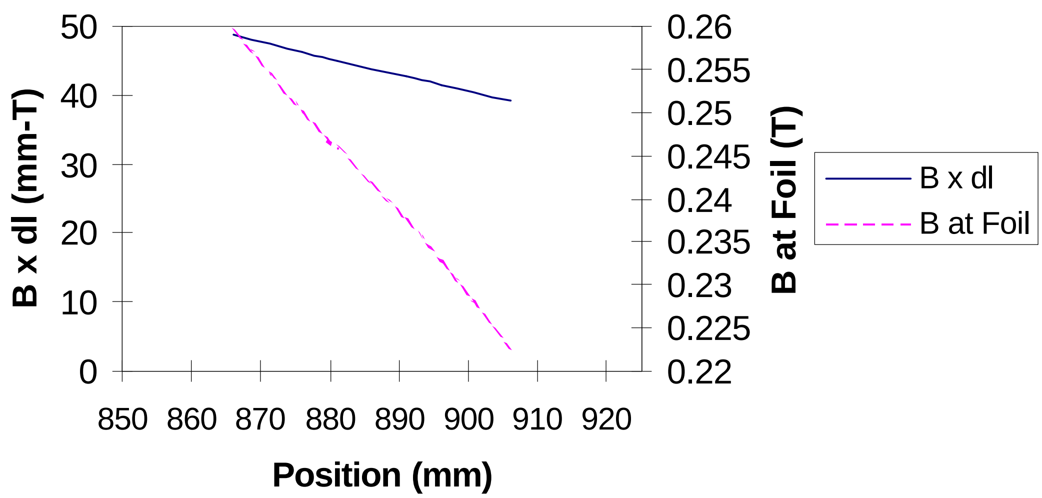

Fig. 7 SNS fringe field profile in the injection foil region. The nominal foil location is at a position of 875 mm, which provides a bend of 46 mm-T in the fringe field downstream from the foil.

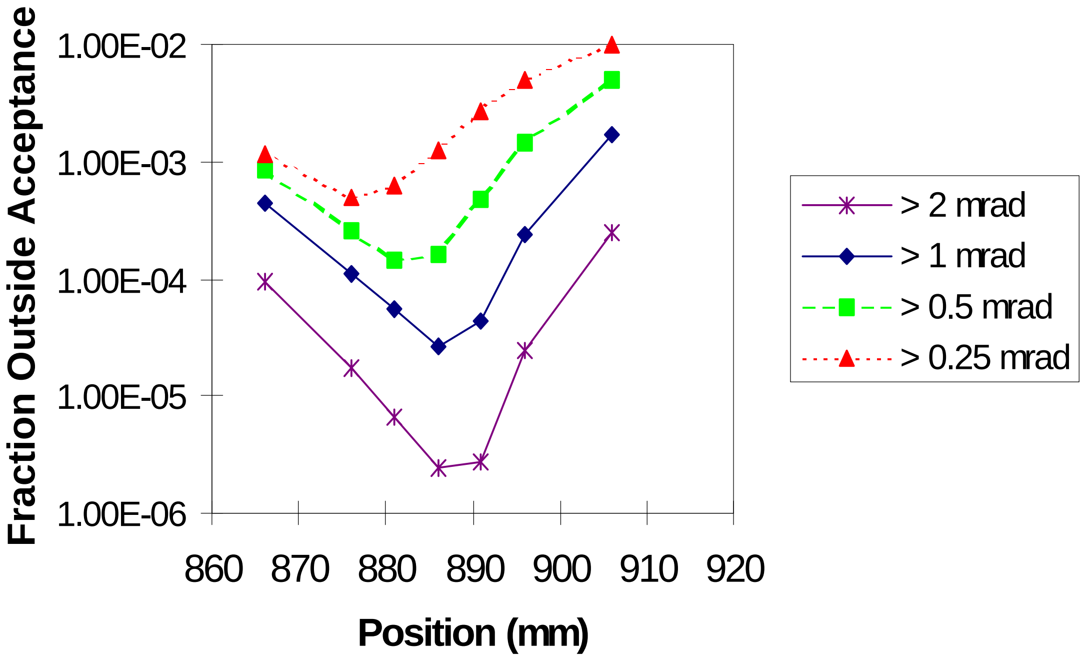

Fig. 8 Loss fractions for a foil located in a fringe field of a tapered-edge dipole with a maximum field of 0.31 T. Losses are shown for several loss criteria. The nominal foil location is at 875 mm.

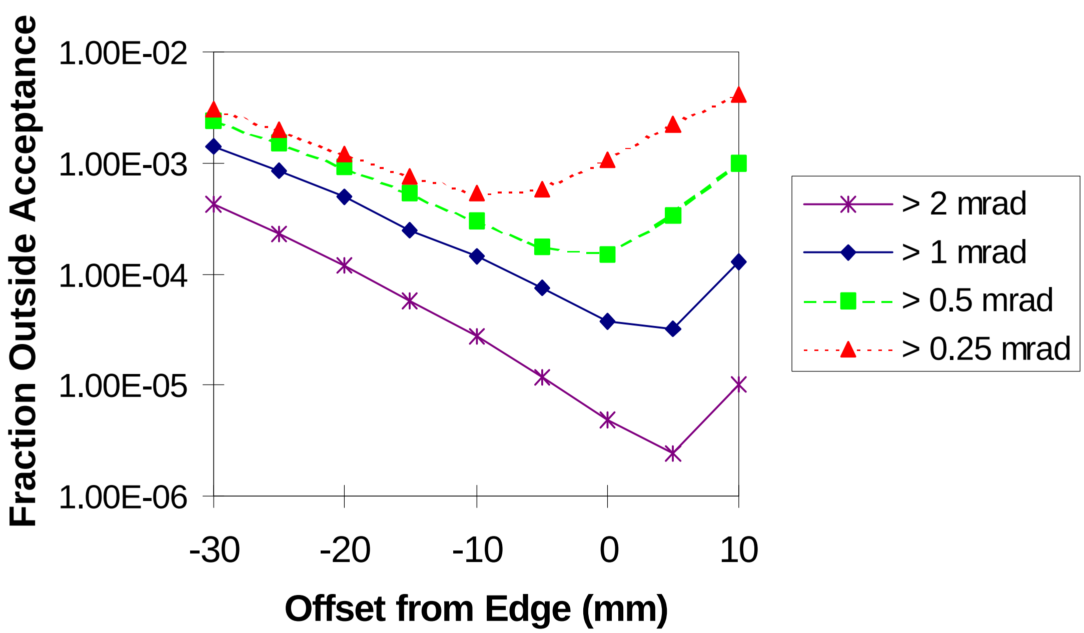

Fig. 9 Loss fractions for a foil located in a fringe field of a sharp-edge dipole with a maximum field of 0.31 T. Losses are shown for several loss criteria. An offset of –24 mm provides the required 46 mm-T bend.

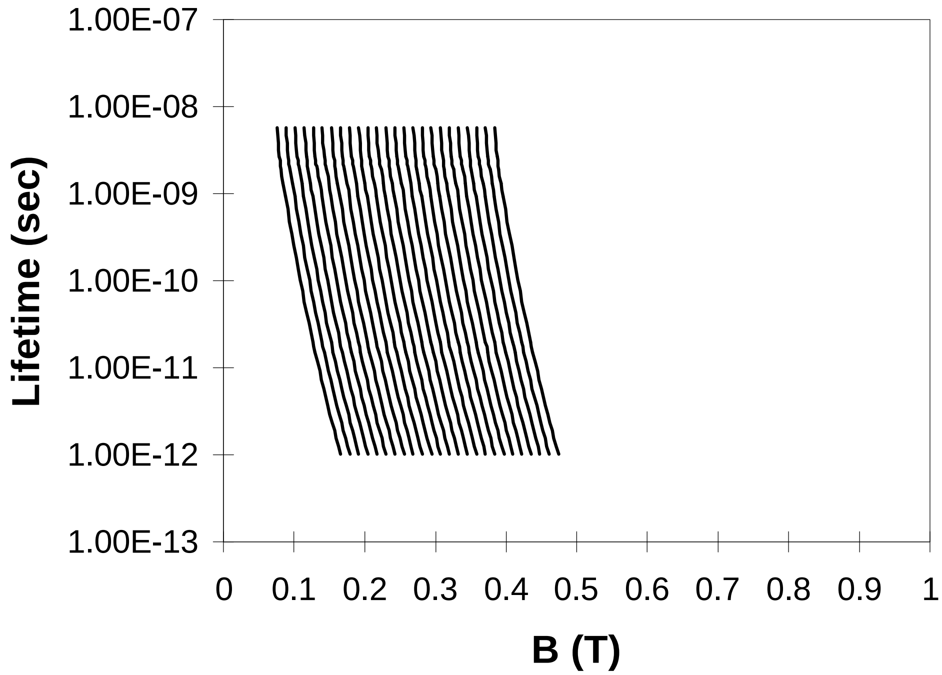

Fig. 10 Artificial uniformly distributed n = 4 and 5 state lifetimes used in sensitivity studies.

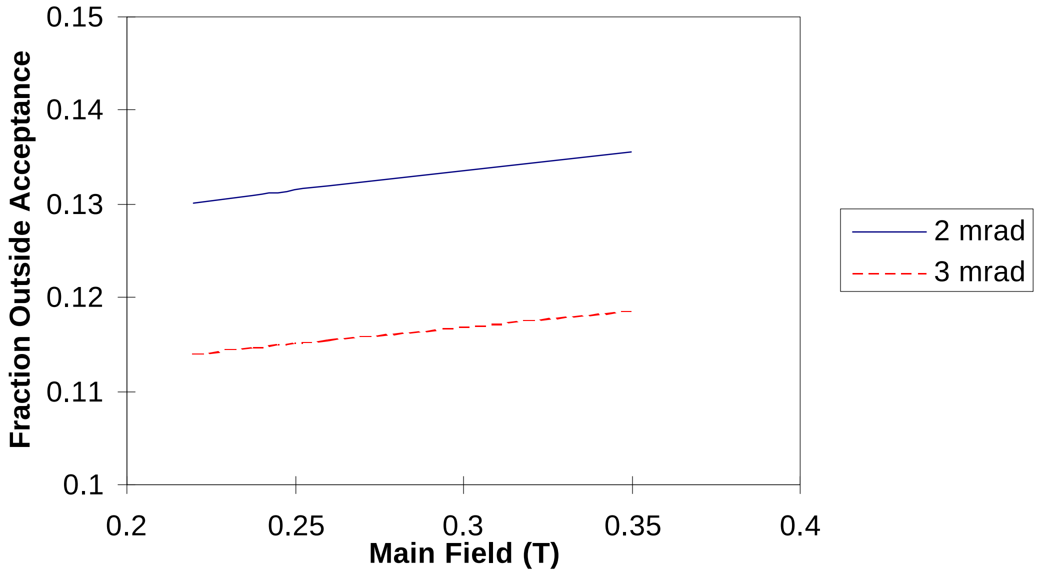

Fig. 11 Loss fractions of "n = 4 and 5 states" for a foil located in a constant magnetic field with the artificially distributed lifetimes shown in Fig. 10. Loss criteria of 2 and 3 mrad are used.

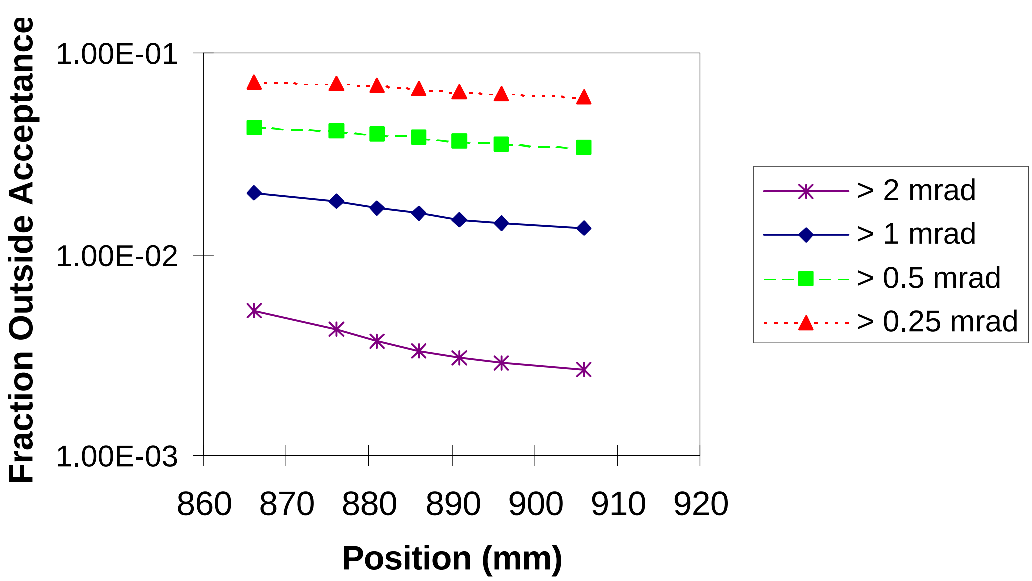

Fig. 12 Loss fractions of n = 4 and 5 states for a foil located in a tapered-edge dipole magnetic field with the artificially distributed lifetimes shown in Fig. 10. Cases with loss criteria ranging from 0.25 to 2 mrad are shown.